TRIAXIAL TESTING OF BITUMINOUS MIXTURES AT HIGH CONFINING PRESSURES

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by

J. C. Oppenlander

&

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Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

TECHNICAL PAPER

TRIAXIAL TESTING OF BITUMINOUS MIXTURES AT HIGH CONFINING PRESSURES

TO: K. B. Woods, Director
Joint Highway Research Project

December 18, 1957

FROM: H. L. Michael, Assistant Director

File: 2-4-11
Project C-36-6K

Attached is a paper entitled, "Triaxial Testing of Bituminous Mixtures at High Confining Pressures," by J. C. Oppenlander and W. H. Goetz. This paper will be presented at the 37th Annual Meeting of the Highway Research Board in Washington, D. C. in January, 1958.

The paper is a summary of a laboratory study previously reported to this Board and contributes to a better understanding of the basic factors that effect the development of shearing strength in bituminous aggregate mixtures.

The paper is presented for the record.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Assistant Director
Joint Highway Research Project

HLM:hgb

Attachment

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TECHNICAL PAPER

TRIAXIAL TESTING OF BITUMINOUS MIXTURES AT HIGH CONFINING PRESSURES

by

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Joint Highway Research Project
File: 2-4-11
Project C-36-6K

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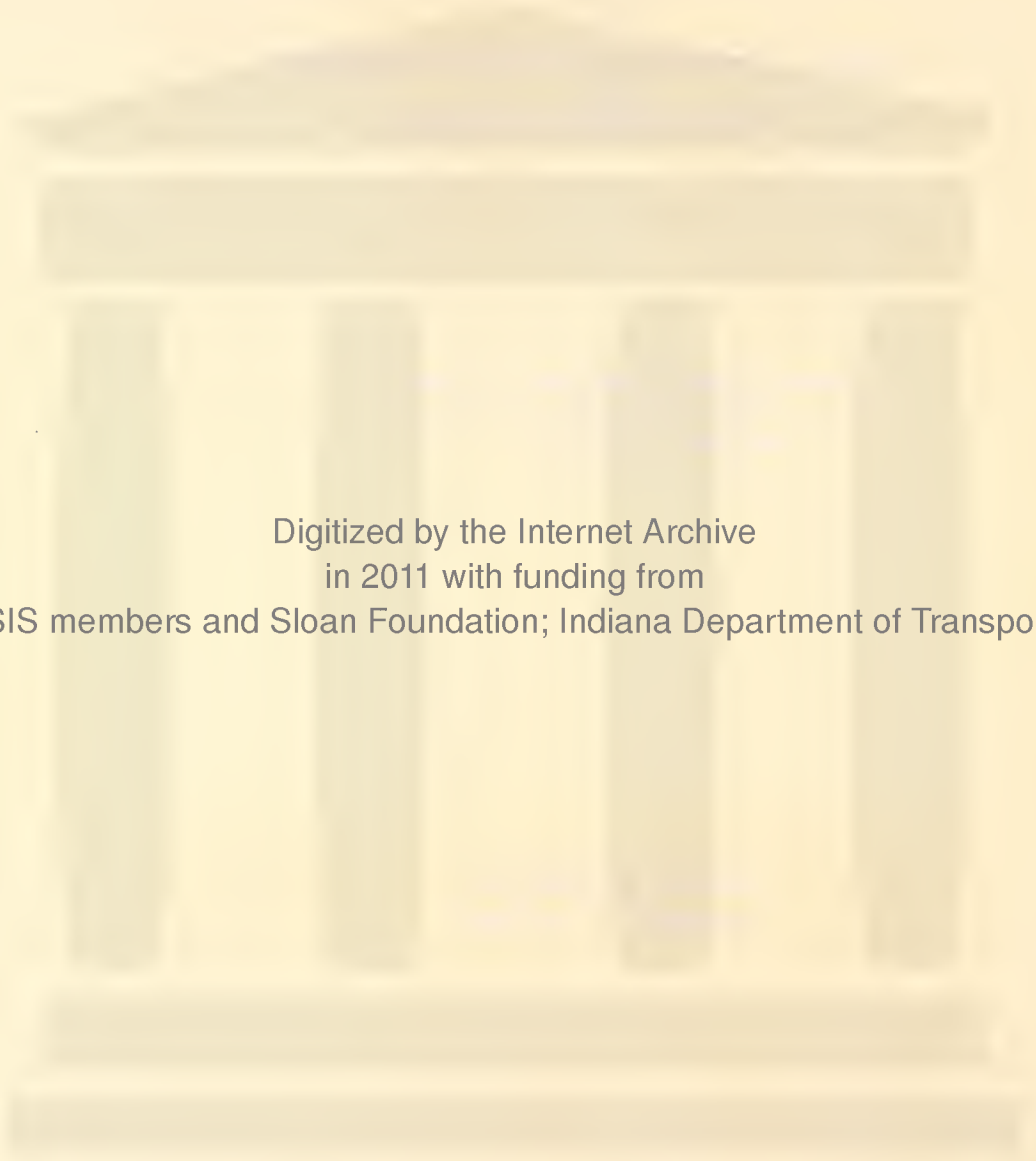
December 18, 1957



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SYNOPSIS

This laboratory study investigated the triaxial testing of bituminous mixtures at high confining pressures. The object of this research was to develop a better understanding of the basic factors that contribute to the development of shearing strength in bituminous-aggregate mixtures.

Two aggregate gradations were used. They were referred to as open-graded and one-size, and were incorporated with an asphalt cement into bituminous mixtures. The open-graded and one-size mixtures were chosen because they both perform satisfactorily as paving mixtures for many service conditions, but only the open-graded mixture possesses adequate stability when evaluated by conventional testing methods. In addition to aggregate gradation, the other variables considered in this investigation were confining pressure, specimen height, type of aggregate, and asphalt content.

The triaxial compression test was selected to measure the shearing resistance of these bituminous-aggregate mixtures at a range of confining pressures from 0 to 150 psi. The rational triaxial test provided a fundamental means for the determination of the various factors that contribute to the stability of bituminous mixtures. However, test specimens having a height to diameter ratio less than two also were fabricated in order to measure the influence of specimen height on the triaxial stability at high confining pressures. This phase of the research investigation was designated as the irrational triaxial test.

For both the rational and the irrational triaxial tests, the open-graded mixture showed strength properties with a direct correlation

to the Coulomb equation. Therefore, the strength properties of this mixture may be represented by the two constants, (c) cohesion and (ϕ) angle of internal friction. However, the shearing strength values produced by the irrational triaxial test were higher than the corresponding values for the rational triaxial test, and different values of cohesion and angle of internal friction were obtained by the two testing procedures.

The triaxial testing of the one-size mixture indicated that a curvilinear relationship existed between the confining pressure and the normal stress. Thus, the shearing strength of this one-size mixture cannot be ascertained wholly by such constants as the cohesion and the angle of internal friction.

For specimens made from both aggregate gradations, the crushed-limestone aggregate produced higher triaxial stability values than the uncrushed gravel and natural sand for the range of confining pressures used. However, the selection of an asphalt content giving maximum strength for these two aggregate types in both the open-graded and the one-size mixtures was determined to be independent of the degree of the confining pressure.

INTRODUCTION

Of those mechanical testing methods most utilized in laboratory studies of the stability of bituminous paving mixtures, the triaxial compression test has proved to be one of the most effective, particularly from the standpoint of research. The data obtained from a triaxial test are usually analyzed in terms of the basic properties, the cohesion and the angle of internal friction, of a cohesive-granular mixture according to Mohr's theory of strength. This theory is thought to be more nearly in accordance with the behavior of bituminous mixtures than any of the other theories applicable to the strength properties of a cohesive-granular material. The triaxial compression test provides a basic and rational approach to the evaluation of the fundamental strength properties of bituminous-aggregate mixtures, while other test methods frequently employed for mix-design purposes provide only an empirical approximation to the expected stability of these paving mixtures. A rational triaxial test is described as a triaxial compression test in which the diameter of the specimen is at least four times the maximum particle size, and the height of the specimen is at least two times its diameter. If the height to diameter ratio of the specimen is less than two, the triaxial compression test is defined as an irrational or a modified triaxial test.

For the purposes of this paper, a "one-size" aggregate is a material which passes the 3/4-inch sieve and is retained on the No. 4 sieve. An "open-graded" aggregate is one that is well graded from coarse to fine without any material passing the No. 200 mesh sieve. From field observation, bituminous mixtures with both "one-size" and "open-graded" aggregate gradations appear to perform satisfactorily for many service conditions. The

results of conventional triaxial testing, on the other hand, show these one-size mixtures to be unstable under present design criteria, while the open-graded mixtures produce acceptable stability values. This illustrates that the present methods and theories of rational triaxial testing as applied to bituminous mixtures with a one-size aggregate fail to evaluate the true in-service stability properties of this paving mixture.

Triaxial compression tests on bituminous-aggregate mixtures have been performed within a relatively low range of confining pressures (up to 60 psi), and the strength properties of these bituminous mixtures have been predicated mainly on the assumption that the Mohr rupture envelopes were straight lines. With the present-day tire pressures of 100 psi for trucks and 200 psi for airplanes and the probable future increase in these values, the lateral support that is provided the bituminous-aggregate mixtures is certainly in excess of the confining pressures used in many triaxial tests performed for bituminous mix design.

The various factors that contribute to this lateral support of the bituminous-mixture surface of the flexible pavement are the tire pressure, the lateral support of the pavement adjacent to the loaded area, and the frictional resistance between the pavement and the tire and between the pavement and the base (12, 15). If certain bituminous-aggregate mixtures are tested with a considerable range of confining pressures, the Mohr rupture envelopes may tend to curve. Depending upon the degree of this curvature, these non-isotropic mixtures may be analyzed by assuming either a straight or a curved Mohr rupture envelope. At present, there is not sufficient information available concerning the rational triaxial testing of bituminous mixtures to ascertain which types of mixtures have straight-line Mohr

rupture envelopes and which ones have curved Mohr envelopes. The rational design of bituminous paving mixtures with curved Mohr envelopes has been developed theoretically by N. W. McLeod (13, 14).

This study, then, investigated the triaxial stability properties of one-size and open-graded bituminous mixtures for a range of confining pressures up to 150 psi. The procedure consisted primarily of carefully testing laboratory-compacted specimens by the open-system triaxial compression test to determine their stability under the influence of different variables. The variable conditions introduced were aggregate gradation, confining pressure, specimen height, type of aggregate, and asphalt content.

MATERIALS

The mineral aggregates selected for this research project were obtained from two commercial aggregate companies, and their physical characteristics were not altered in the laboratory except for the gradation. Both the coarse and the fine aggregate fractions used in the individual bituminous mixtures were of the same aggregate type, either crushed limestone or uncrushed gravel and natural sand.

The procedures outlined in the ASTM Standards (2) were followed in the determination of the specific gravity and absorption values of these materials. Standard test method C127-42 applied to the coarse aggregate, while standard test method C128-42 was applicable to the fine-aggregate fraction. The results of these tests are shown below:

Specific Gravity and Absorption of Aggregate

Aggregate	Bulk Sp Gr	Apparent Sp Gr	% Absorption
Crushed Limestone	2.66	2.71	0.74
Uncrushed Gravel	2.60	2.74	2.00
Natural Sand	2.54	2.68	2.04

As previously mentioned, one of the variables in this investigation was the gradation of the aggregate. The open-graded aggregate corresponded to the requirements for the Hot Asphaltic Concrete Binder Course, and the one-size aggregate followed the Bituminous Coated Aggregate Surface Course (size No. 9 aggregate), as presented in the Indiana State Highway Department Specifications (17). Samples of these two gradations are pictured in Figure 1 for the crushed-limestone aggregate and in Figure 2 for the uncrushed-gravel and natural-sand aggregate. The sieve analyses of these open-graded and one-size aggregates are presented in Table 1.

A graphical plot of the gradation of these two aggregates is shown by the aggregate gradation curves in Figure 3.

The bituminous material used in this study was an asphalt cement classified as a 60-70 penetration grade, having a penetration of 66, a specific gravity of 1.018, and a ductility at 77 F and 5 cm/min of over 150 cm. The asphalt contents for the different aggregate gradings were maintained at 5.0 percent by weight of the total mixture throughout most of this research investigation. These percentages of asphalt cement used in the open-graded and the one-size aggregate mixtures were those normally specified for actual construction by the Indiana State Highway Department.

In one phase of this research study, the asphalt contents of the open-graded specimens and the one-size specimens were altered to furnish information concerning the effects of asphalt content on the triaxial stability values of these two differently-graded specimens tested at a range of confining pressures. The various asphalt contents used in the open-graded and the one-size compacted bituminous-aggregate specimens were as follows:

Asphalt Contents for Different Aggregate Gradations

Aggregate Gradation	Asphalt Content (Percent of total mixture weight)
Open-graded	4.0, 5.0, 6.0
One-size	3.0, 4.0, 5.0

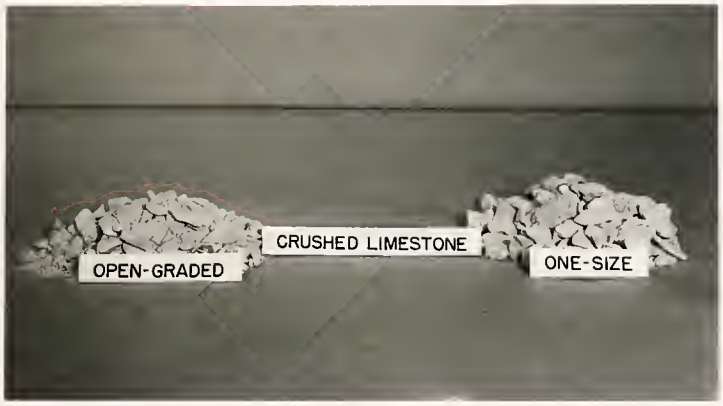

Figure 1 Crushed Limestone Aggregate, Open-Graded and One-Size Gradations

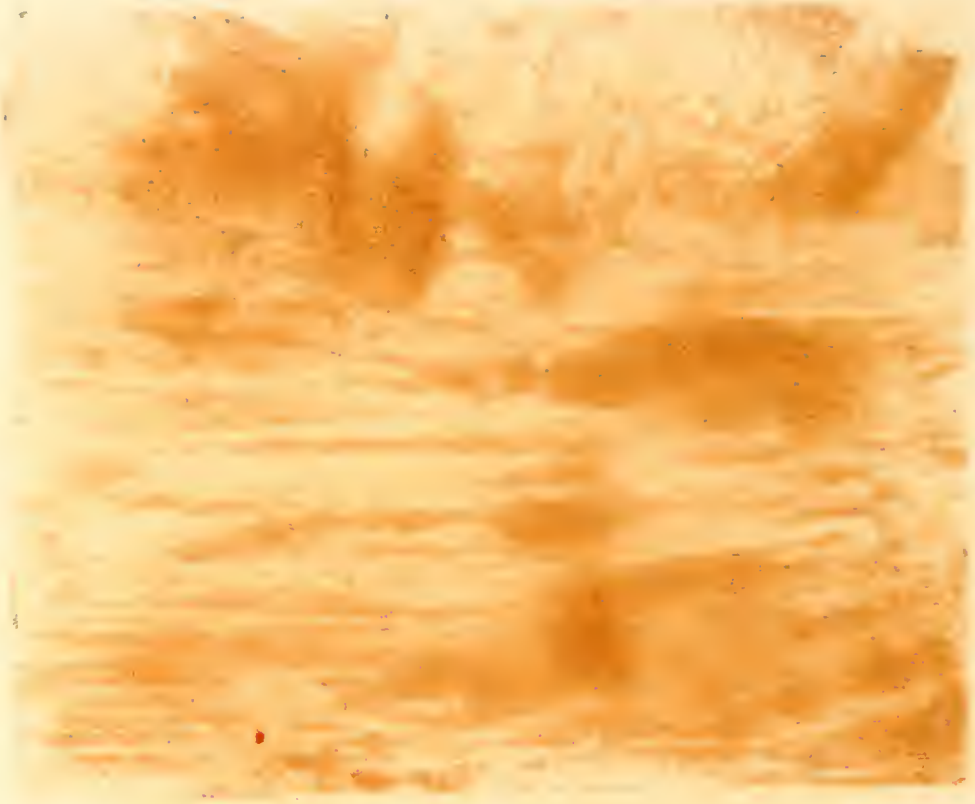

Figure 2 Uncrushed Gravel and Natural Sand Aggregate
Open-Graded and One-Size Gradations

TABLE 1

Grading of Open-Graded and One-Size Aggregates

(Percent by Weight)

SIEVE		GRADING	
PASSING	RETAINED	OPEN	ONE-SIZE
---	3/4"	0	0
3/4"	1/2"	17.5	29.2
1/2"	3/8"	21.4	35.4
3/8"	#4	21.4	35.4
#4	#6	2.9	0
#6	#8	1.7	0
#8	#16	10.5	0
#16	#50	20.7	0
#50	#100	3.6	0
#100	#200	0.3	0
#200	---	0	0

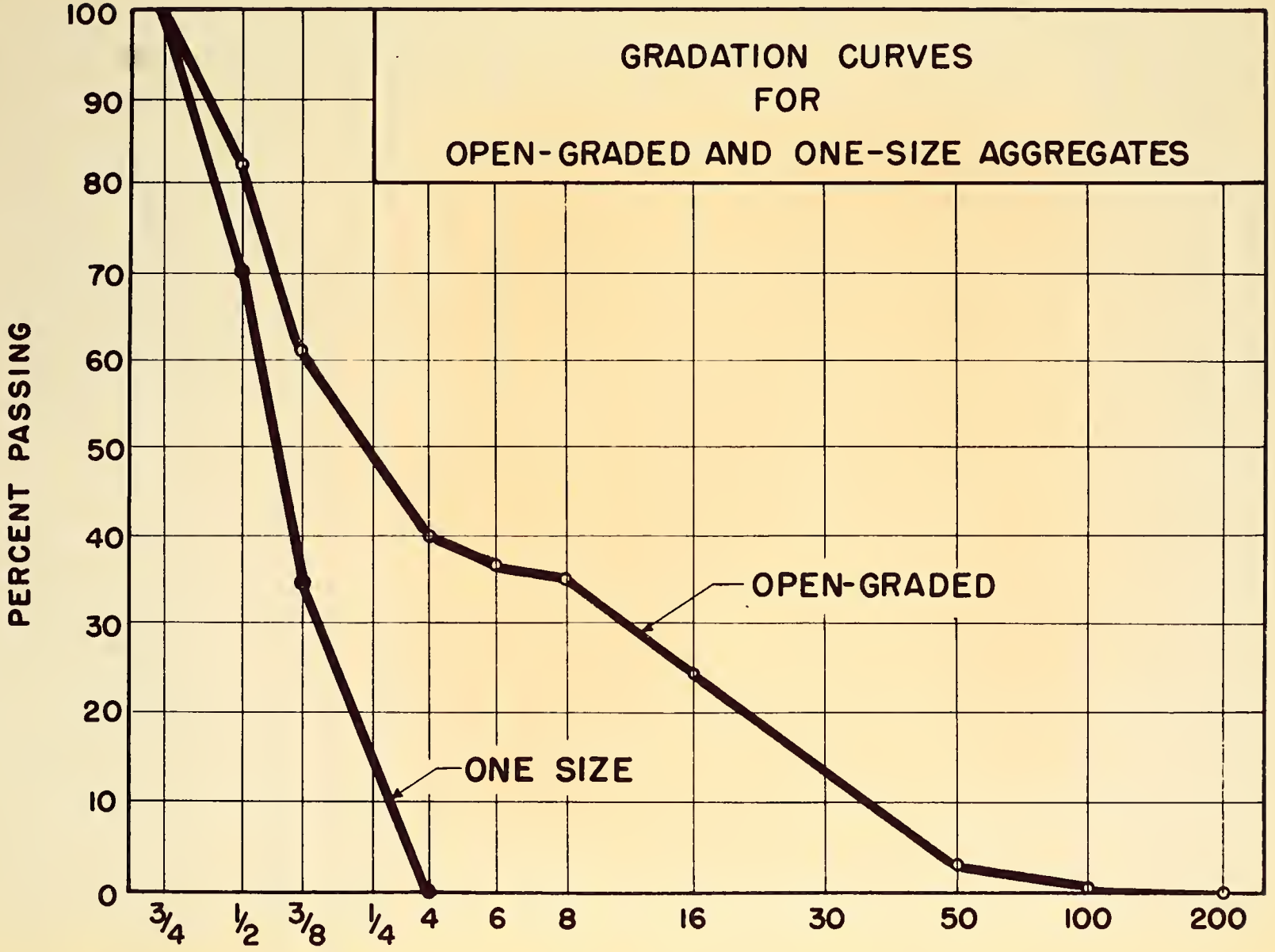
GRADATION CURVES
FOR
OPEN-GRADED AND ONE-SIZE AGGREGATES
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
OPEN-GRADED
ONE SIZE
3/4
1/2
3/8
1/4
4
6
8
16
30
50
100
200
SIEVE SIZE (LOG SCALE)

FIG. 3

PROCEDURE

In order to provide a high degree of control over the aggregate gradations, the mineral aggregates were separated into various sieve size fractions as given in Table 1 and then were recombined in the desired proportions just prior to the preparation of the test specimens.

The preparation of the test specimens of the open-graded type consisted of the following procedure. With the prepared aggregate and the asphalt cement heated to the temperatures of 300 ± 10 F and 275 ± 10 F respectively, these two components of a bituminous mixture were incorporated in a heated bowl with a Hobart mixer for a period of two minutes. This bitumous-aggregate mixture was then placed in a heated compaction mold in equal layers, four layers for the rational test specimens and two layers for the irrational test specimens. Each layer was rodded 25 times with a 3/4-inch round steel bar that weighed 1.4 lb. The triaxial test specimen was compacted by the double-plunger method with a pressure of approximately 2170 psi on each end of the specimen. After this pressure was maintained constant for one minute, the compaction mold containing the compacted specimen was immersed in a circulating cold-water bath for a period of 8 to 12 minutes. Upon the completion of the cooling period, the specimen was removed by disassembling the compaction mold. The open-graded specimens (see Figure 4) were placed in a convenient storage area at room temperature until the time for testing.

The preparation of the one-size test specimens was accomplished by the same prescribed methods except for certain modifications. The aggregate and the asphalt cement were heated to the temperatures of 200 ± 10 F and 235 ± 10 F, respectively, before the mixing operation. During the compaction

of this bituminous mixture by the double-plunger method, a pressure of only 430 psi was applied to each end of the specimen to reduce the amount of aggregate breakage. To provide better compaction, the compaction mold was vibrated by striking it with a leather mallet for 50 blows, while the compacting pressure was maintained. After the test specimen was removed from the cooled compaction mold, a light-weight, sheet metal container was placed around the specimen. These containers were not removed until the specimens were to be tested. A one-size mixture specimen and a sheet metal container are illustrated in Figure 4.

After the density values of the compacted specimens were determined, they were tested by the triaxial compression test of the open-system type. These triaxial tests were performed on identical specimens for a range of confining pressures (0 to 150 psi at 30 psi intervals) that were maintained constant for the duration of the test. The compacted specimens were deformed at the uniform rate of 0.05 in. per min. within a temperature range of 77 $\pm$ 5 F. General views of the complete assembly for the triaxial compression test are shown in Figure 5 for the rational test and in Figure 6 for the irrational or modified test.

During the triaxial compression test of the open-graded specimens, the volume of the sample remained constant. However, the one-size specimens experienced a measurable reduction in volume when they were subjected to the triaxial compression test. Since a measure of this volume change was required for the proper reduction of the triaxial test data, the volume of the specimen both before and after the test was determined.

A stress-strain diagram was prepared for each triaxial test. Values of total normal stress for various percent strains and the peak

Figure 4 Open-Graded and One-Size Mixture Specimens and One-Size Specimen Container

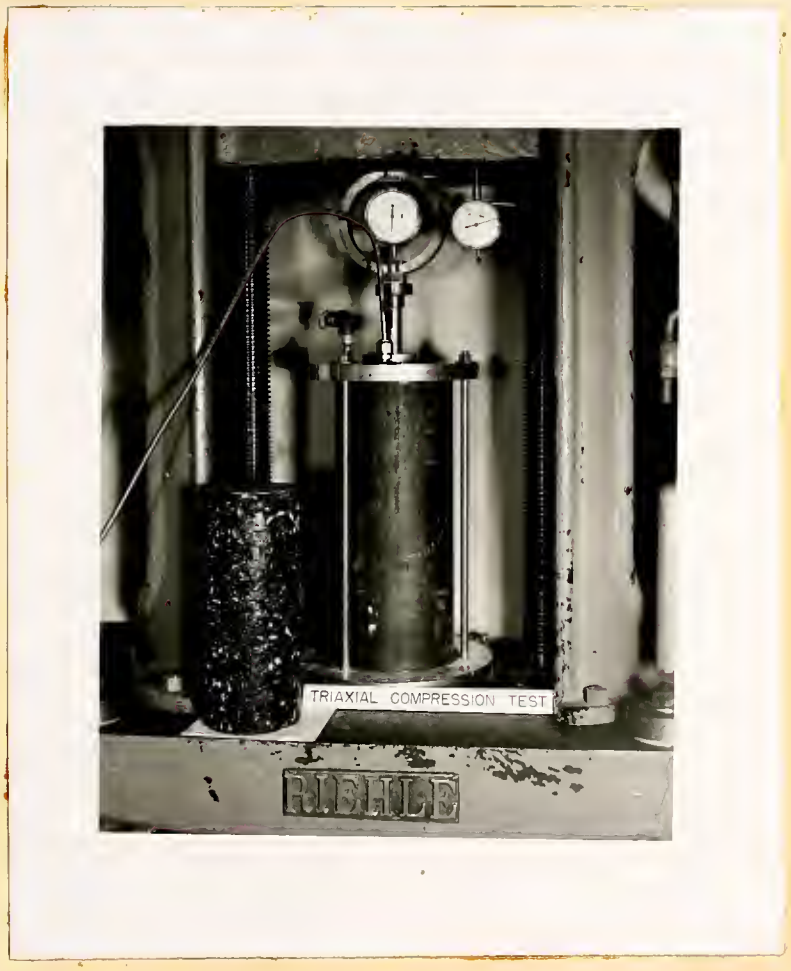

Figure 5 Rational Triaxial Compression Test

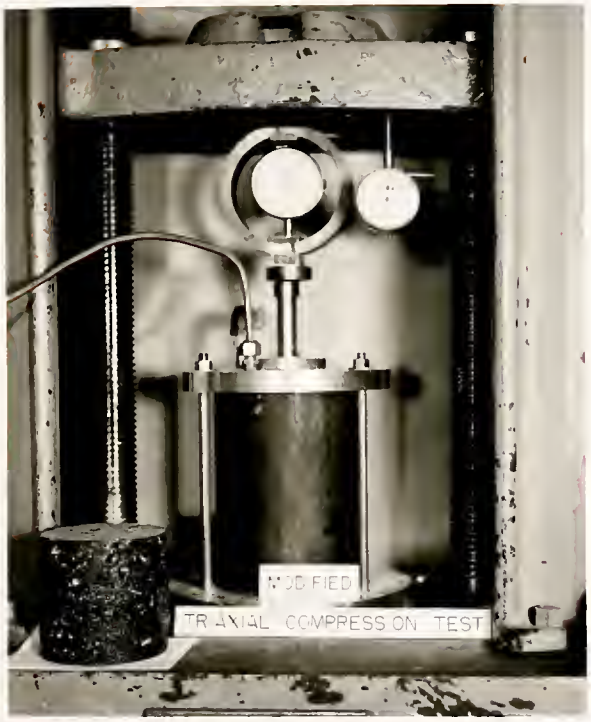

Figure 6 Irrational Triaxial Compression Test

condition (if it existed) were obtained from these stress-strain curves.

A convenient method for analyzing triaxial test results, without plotting the Mohr diagram, is to plot a graph of the confining pressure versus the total normal pressure. This plot will yield a straight line if the Mohr rupture envelope is linear. W. M. Aldous, R. C. Herner, and M. H. Price (1) have derived expressions for determining the angle of internal friction and the cohesion from the slope and the vertical intercept of this graph of the lateral and normal stresses. Although the utilization of these two equations is only applicable to isotropic bituminous mixtures having a linear Mohr rupture envelope, the plot of the confining pressure versus the total normal stress provides a convenient, graphical analysis of the strength properties of non-isotropic bituminous-aggregate mixtures (6) having curved Mohr rupture envelopes. For these cases, the plots will be curved, and values of the angle of internal friction and cohesion will vary for different confining pressures.

RESULTS

In this laboratory investigation, triaxial stability values were determined for compacted bituminous mixtures by the open-system triaxial compression test using confining pressures up to 150 psi. The variable conditions introduced were aggregate gradation, confining pressure, specimen height, type of aggregate, and asphalt content.

The selection of the two main divisions, open-graded mixture and one-size mixture, for this research report is based on the findings that the stress-strain curves representing these two bituminous mixtures were considerably different. As shown in Figure 7, the stress-strain curves for the open-graded mixture reached a peak normal stress value at a relatively low strain value, while the normal stress continued to increase at a decreasing rate with an increase in the strain value for the one-size mixture.

TYPICAL STRESS-STRAIN CURVES

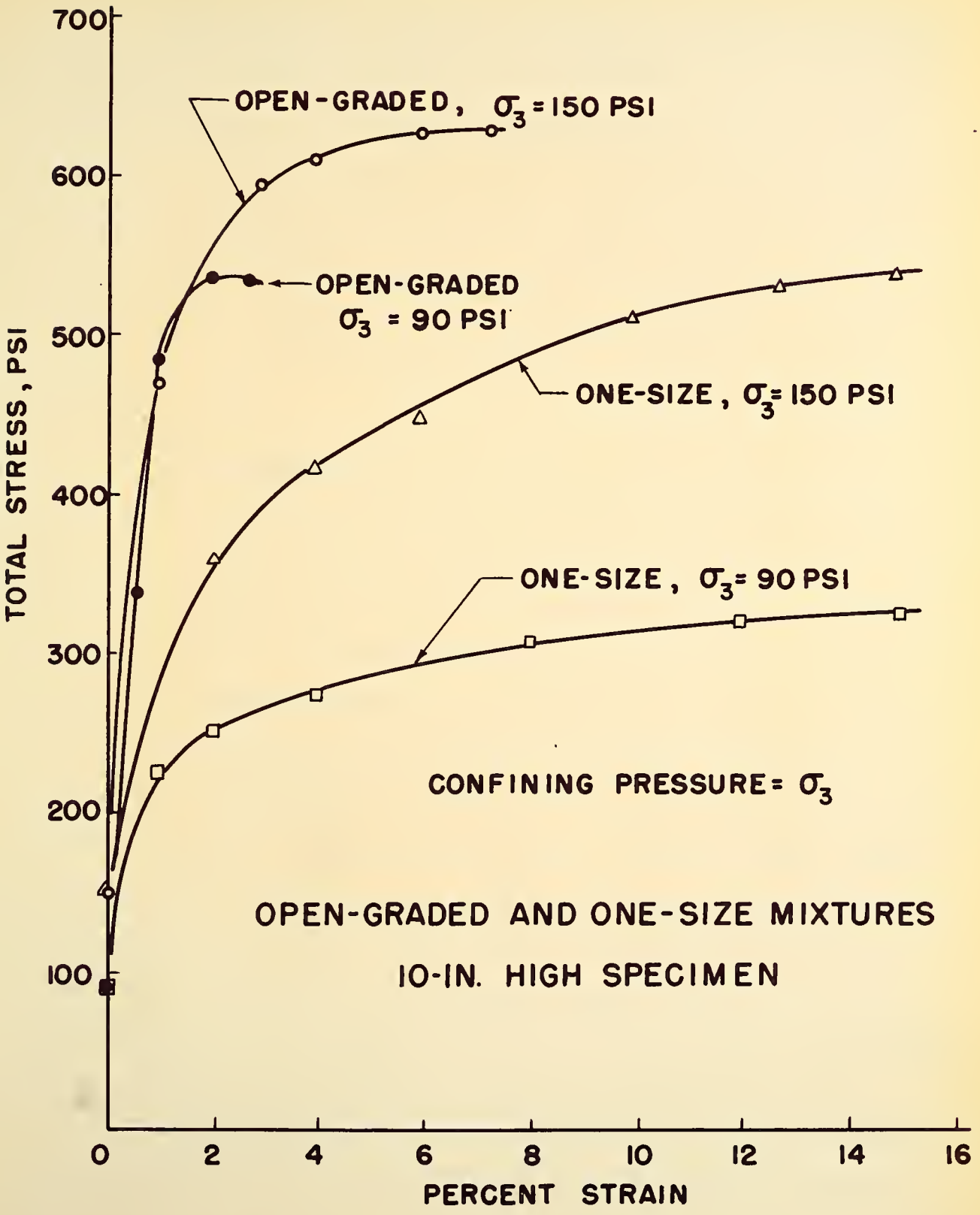

FIG. 7.

Open-Graded Mixture

The triaxial test results on the open-graded mixture are presented in Table 2 for the rational triaxial test, and Table 3 for the irrational test (See appendix). The shearing resistance of the open-graded paving mixture is illustrated in Figure 8 where the confining pressure versus the peak normal stress was plotted from stress values ascertained from both rational and irrational triaxial tests with confining pressures ranging from 0 to 150 psi, at 30 psi intervals. Crushed limestone was used in this mixture at an asphalt content of 5.0 percent by weight of the total mixture.

Rational Triaxial Text. The results of the rational triaxial tests show that this bituminous-aggregate mixture possessed appreciable triaxial stability, 390 psi, at the low confining pressure of 30 psi. The shearing strength increased linearly with confining pressure until a value in excess of 700 psi was reached at the 150-psi level. Since this linear relationship between confining pressure and peak normal stress is analogous to a straight-line Mohr rupture envelope (1), the shearing strength of this bituminous mixture may be ascertained by the Coulomb equation and represented by the constants (c) cohesion and (ϕ) angle of internal friction. However, the peak normal stress at 0 psi confining pressure did not agree with the linear relationship; thus, indicating that the Mohr rupture envelope is curvilinear in the range of low confining pressures (less than 30 psi). This condition has been validated by previous rational triaxial text investigations in both the soil mechanics and the bituminous-mixture areas.

Specimen Height (Irrational Triaxial Test). The results obtained in evaluating the effects of specimen height on the triaxial stability of

CONFINING PRESSURE VS. PEAK NORMAL STRESS

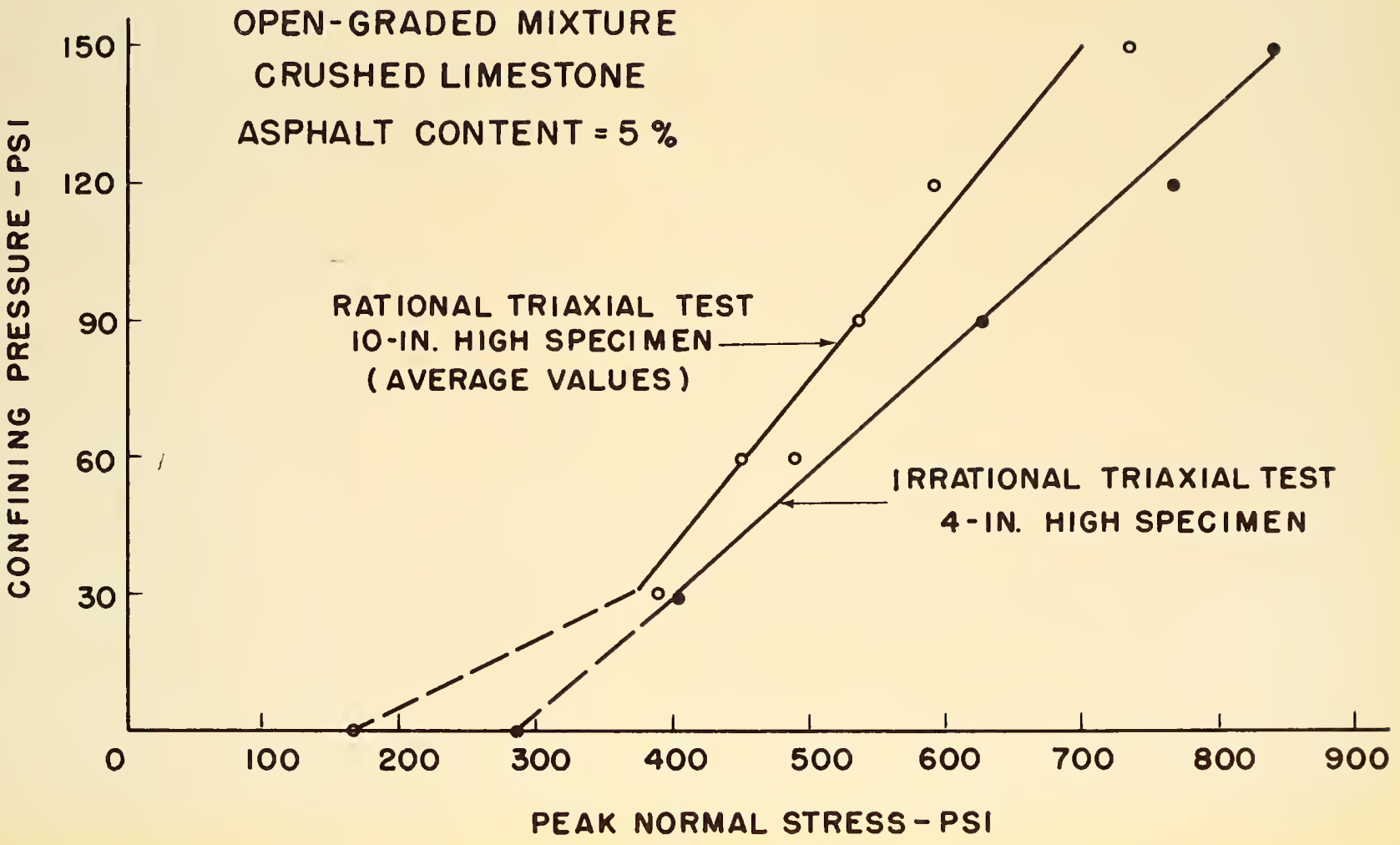

FIG. 8

bituminous paving mixtures tested at high confining pressures also are presented in Figure 8. The relationship between the plotted stress values was best represented by a straight line. These irrational triaxial tests were performed on compacted bituminous specimens having the same type of aggregate and the same asphalt content as the specimens used in the previously discussed rational triaxial test, except that 4-in. high specimens were used (height to diameter ratio was less than two). For corresponding confining pressures, the peak normal stresses obtained in the irrational triaxial tests were greater than those stresses determined in the rational triaxial testing. This result was produced by the additional lateral support afforded the irrational test specimen by the shearing stresses developed between the ends of the specimen and the upper and the lower loading plates. This reasoning also explains the close position of the peak normal stress for the 0 psi confining pressure to the extension of the straight line representing the irrational triaxial tests in Figure 8.

For both the rational and the irrational triaxial tests of the open-graded mixtures, the peak normal stresses were reached at strain values of six percent or less. The strains at which the peak stability values occurred centered around one or two percent for the 30 psi confining pressure, and they gradually increased with an increase in the confining pressure to the 150-psi level where the strain values were near six percent (see Figure 7).

Although the two series of test values plotted in Figure 8 appear to be characterized by a linear relationship, the slopes of these two straight lines are different. This indicates that the rational and

the irrational triaxial tests do not produce equal measures of the strength properties, cohesion, and angle of internal friction of this open-graded mixture.

Type of Aggregate. To evaluate the variable of aggregate type for rational triaxial testing at high confining pressures, 10-in. high specimens of the open-graded mixture were formed from uncrushed gravel and natural sand at asphalt contents of 4.0 and 5.0 percent by weight of the total mixture. A comparison of the triaxial strengths of these specimens with those values obtained from crushed-limestone specimens having identical asphalt contents is presented in Figure 9 for the confining pressures of 30, 90, and 150 psi. The greater shearing strength exhibited by the crushed-limestone mixture for the range of confining pressures was attributed to the larger degree of interlocking among these angular aggregate particles as compared to the uncrushed material.

With respect to the effect of confining pressure on the relative shearing resistance values of these specimens made from crushed and uncrushed aggregates, it should be noted that the higher the confining pressure, the smaller the difference in strength between comparable specimens. Also, since the shearing strength was greatly increased at higher confining pressures, this difference in strength between comparable specimens expressed as a percentage of the shearing strength of either becomes much less the higher the confining pressure.

Asphalt Content. The effects of high confining pressures on the triaxial stability were determined for the open-graded mixture at asphalt contents of 4.0, 5.0, and 6.0 percent by weight of the total mixture. (The results of these tests are presented in Tables 4 and 5 (Appendix).

CONFINING PRESSURE VS. PEAK NORMAL STRESS

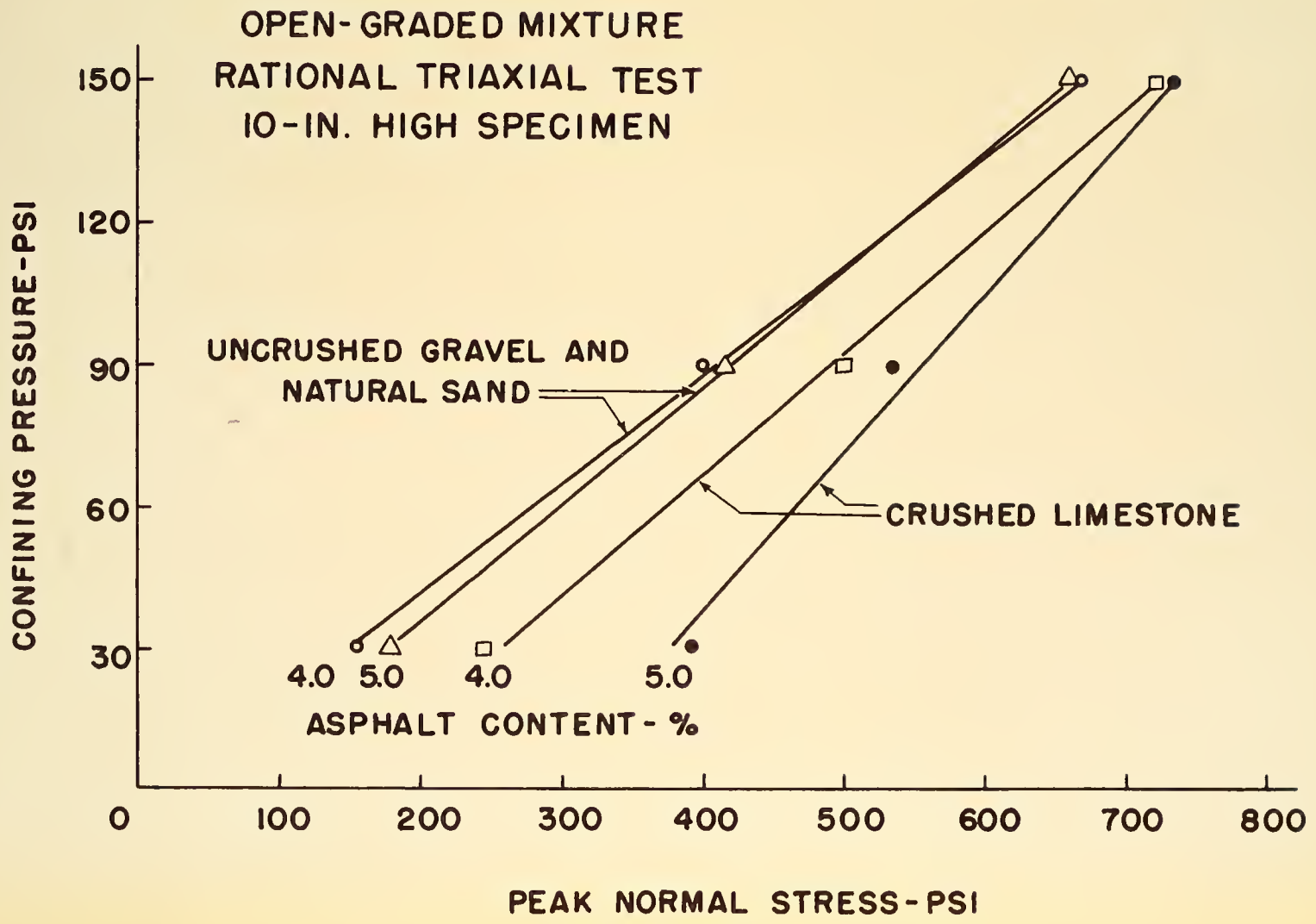

FIG. 9

The results of the rational triaxial tests for the low and high confining pressures of 30 and 150 psi, respectively, are shown in Figure 10 for the crushed-limestone specimens. The analogous case for the uncrushed-gravel and natural-sand specimens is presented in Figure 11. For the open grading of both types of aggregate, it is apparent from these two figures that confining pressure has little or no effect on the determination of the asphalt content producing maximum stability in the triaxial compression test. The asphalt content producing maximum triaxial stability appeared to be near five percent by weight of the total mixture for both the crushed-limestone and the uncrushed-gravel and natural-sand mixtures, whether evaluated at 30 or 150 psi confining pressure.

NORMAL STRESS VS. ASPHALT CONTENT

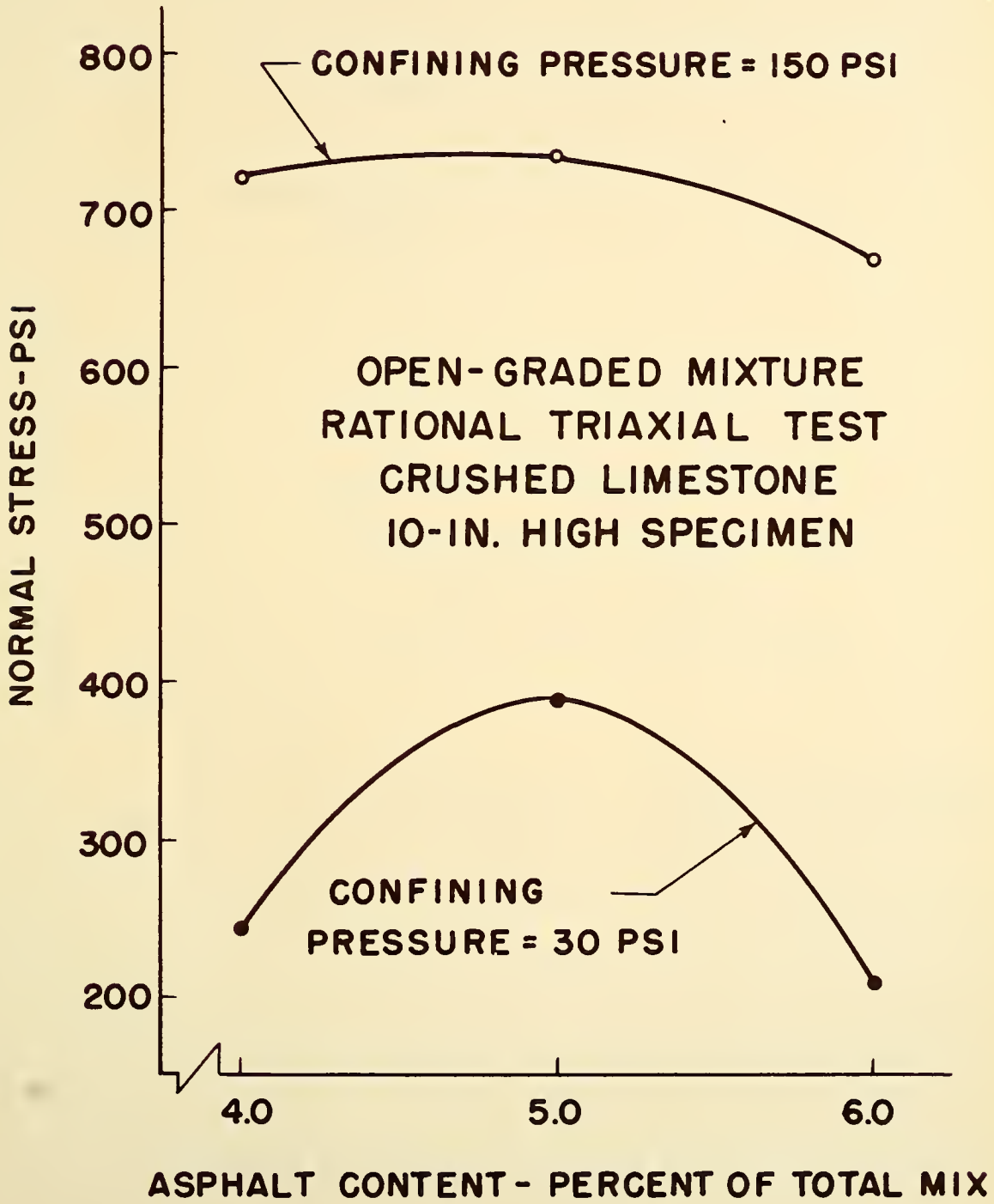

FIG. 10

NORMAL STRESS VS. ASPHALT CONTENT

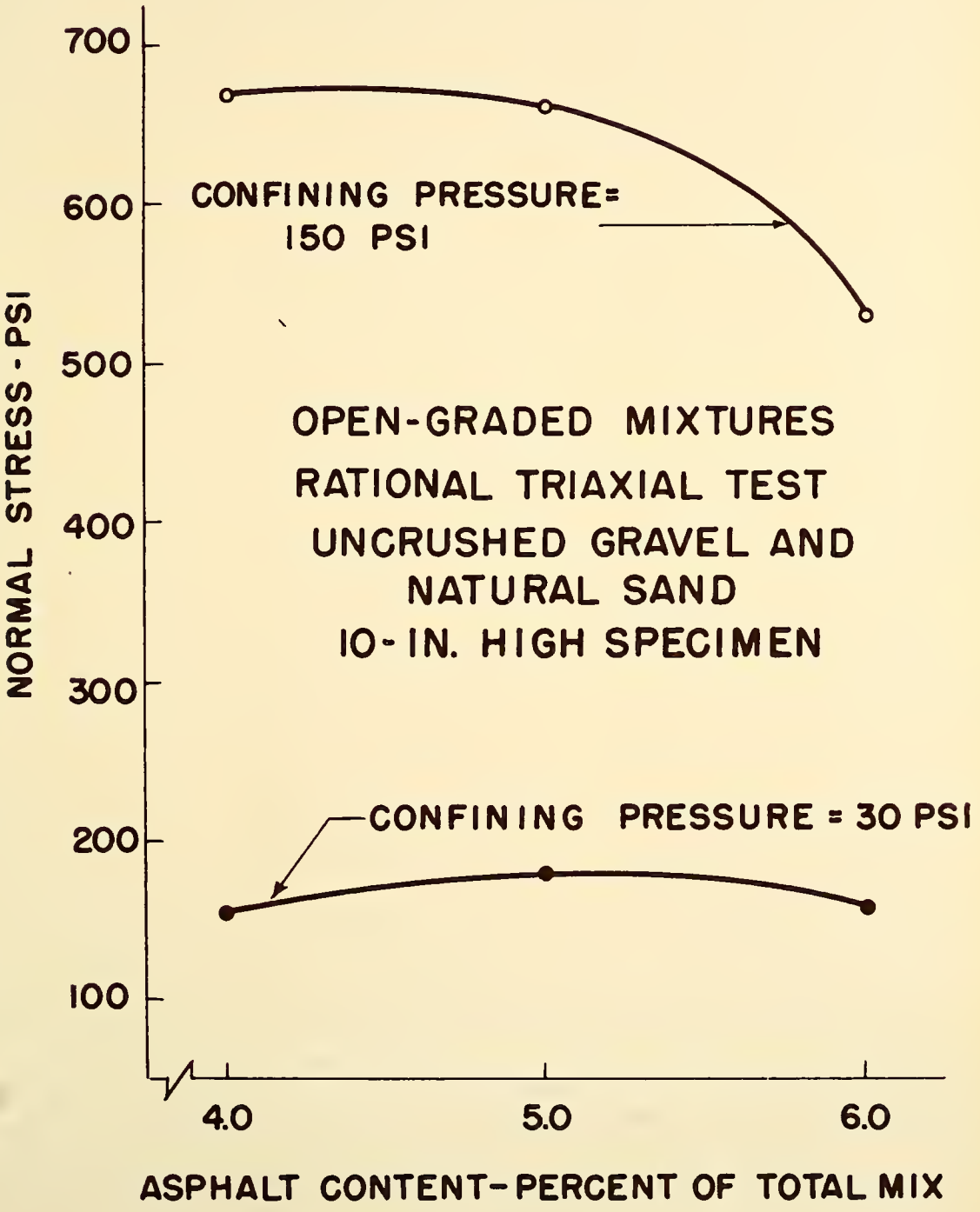

FIG. 11

One-Size Mixture

The other aggregate gradation investigated in this study of triaxial compression testing at high confining pressures was the one-size mixture. The triaxial test results on this mixture are presented in Table 6 for the rational triaxial test and in Table 7 for the irrational test (Appendix). This paving mixture has performed more satisfactorily under traffic than would be predicted by laboratory appraisals for this bituminous-aggregate combination.

Rational Triaxial Test. The development of the shearing strength of this one-size mixture of crushed limestone is illustrated in Figure 12, where the confining pressure versus the normal stress at various percent strain was plotted. These stress values were determined by rational triaxial tests with confining pressures ranging from 0 to 150 psi, at 30 psi intervals, on compacted crushed-limestone specimens having an asphalt content of 5.0 percent by weight of the total mixture. As evidenced by the typical stress-strain curves for this one-size mixture at various confining pressures (see Figure 7), the normal stresses increased at a decreasing rate with an increase in the amount of strain applied to the test specimen. However, this decreasing rate was found to vary inversely with the confining pressure. This is illustrated by comparing the normal stresses at 1.0 and 15.0 percent strain in Figure 12 for the two confining pressures of 30 and 150 psi. Thus, at the 30 psi level shearing strengths of approximately 100 and 160 psi were developed at 1.0 and 15.0 percent strain, respectively; while the corresponding stability values at a confining pressure of 150 psi were 300 and 540 psi. The absence of any peak normal stress for positive confining pressures provoked the

CONFINING PRESSURE VS. NORMAL STRESS AT VARIOUS PERCENT STRAIN

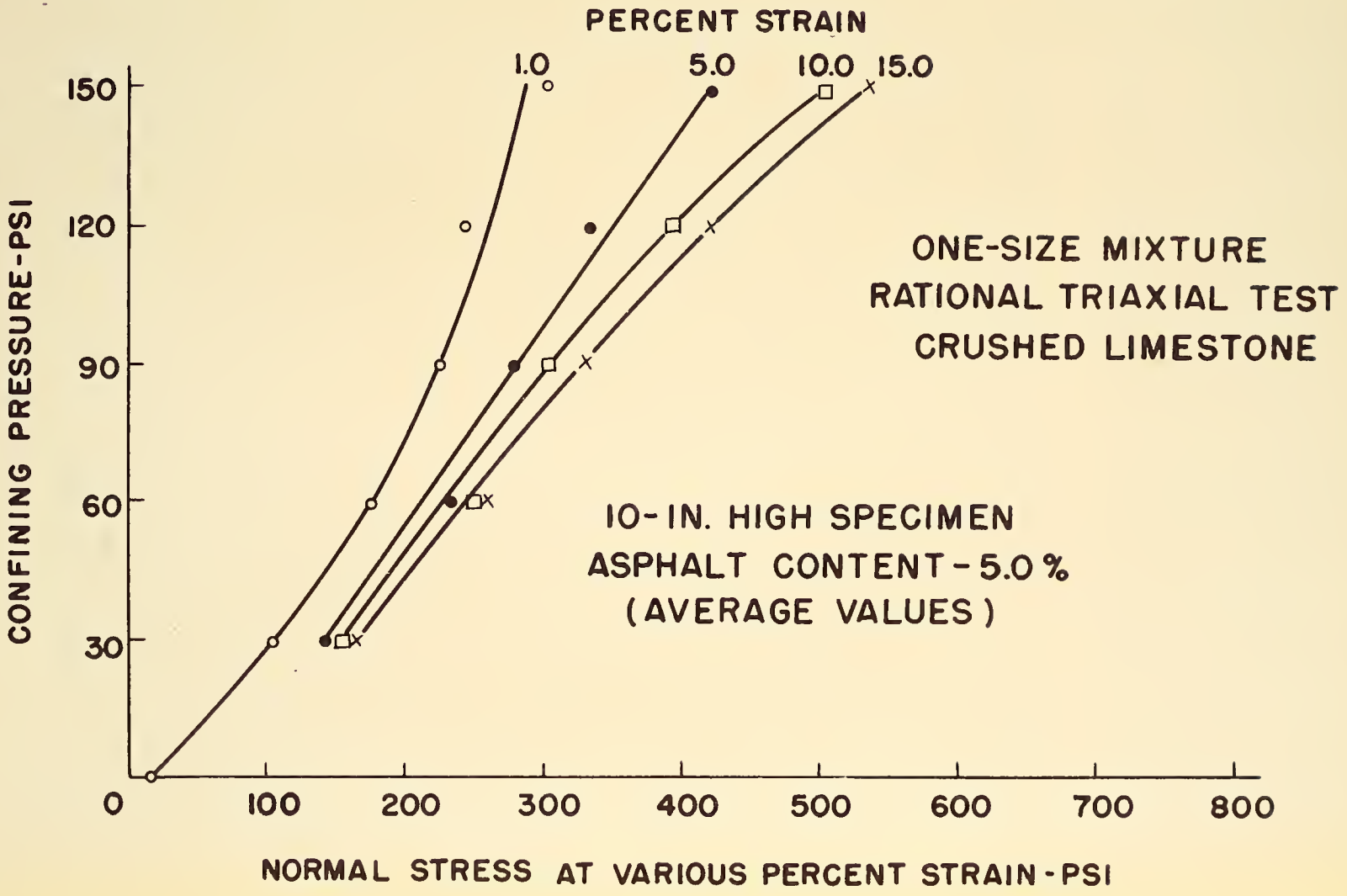

FIG. 12

analyses of the triaxial strength data at 1.0, 5.0, 10.0, and 15.0 percent strain. The physical limitations of the triaxial test apparatus and the difficulty of forming completely homogeneous test specimens of the one-size mixture prevented the determination of normal stress at greater strain values. The value of 15.0 percent strain may also be considered the maximum practical deformation limit for flexible pavement design applications.

The relationship between the confining pressure and normal stress at 1.0, 5.0, 10.0, and 15.0 percent strain for the one-size mixture (see Figure 12) is considerably different than that presented for the open-graded mixture (see Figure 8). The normal stresses at 1.0 percent strain increase at a decreasing rate with an increase in the confining pressure. At the 5.0 percent strain value, the graph of these two stress values is best represented by a straight line. The normal stresses at the larger strains, 10.0 and 15.0 percent, follow a curvilinear pattern in which the normal stresses increase at an increasing rate for an increase in the confining pressure. The variable nature of these stress diagrams indicates that the cohesion and the angle of internal friction were not constants in this one-size mixture when the stability was ascertained by the rational triaxial compression test. The angle of internal friction and/or the cohesion varied throughout the range of confining pressures and the range of strains. Thus, the Coulomb equation and fixed values of cohesion and angle of internal friction cannot truly represent the triaxial stability of this one-size mixture. Since the triaxial compression test on the one-size limestone mixture produced a peak normal stress near 1.0 percent strain for the 0 psi confining pressure condition, the other three sets

of curves must show a reversal in slope in the range of low confining pressures and approach zero at 0 psi confining pressure.

Specimen Height (Irrational Triaxial Test). The effects of specimen height on the triaxial strength of bituminous-aggregate mixtures tested at high confining pressures were investigated for this one-size mixture. The irrational triaxial test results for 4-in. high specimens of crushed limestone are presented graphically in Figure 13. The asphalt content was again maintained at 5.0 percent by weight of the total mixture. The pattern of curves representing the relationship between the confining pressure and the normal stress for the various strains is similar in each case to those representing the stability properties of the rational triaxial specimens. However, the irrational triaxial test data at 1.0 percent strain was best represented by a straight line. At the three higher strain values of 5.0, 10.0, and 15.0 percent, the stress curves show that normal stress increased at an increasing rate as the higher confining pressure was reached.

A comparison of the rational test results as shown in Figure 12 to the irrational test data in Figure 13 indicated that the normal stresses at 30 and 60 psi confining pressure were higher for the rational specimens (10-in. high) than for the irrational specimens (4-in. high), while the reverse was true for the higher confining pressures of 90, 120, and 150 psi. The curvilinear pattern of these relationships between the confining pressure and the normal stress at various strains prevents the analysis of the stability properties in terms of such constant values as the cohesion and the angle of internal friction. Only the shearing stress of this mixture for any given condition of confining pressure and strain

CONFINING PRESSURE VS. NORMAL STRESS AT VARIOUS PERCENT STRAIN

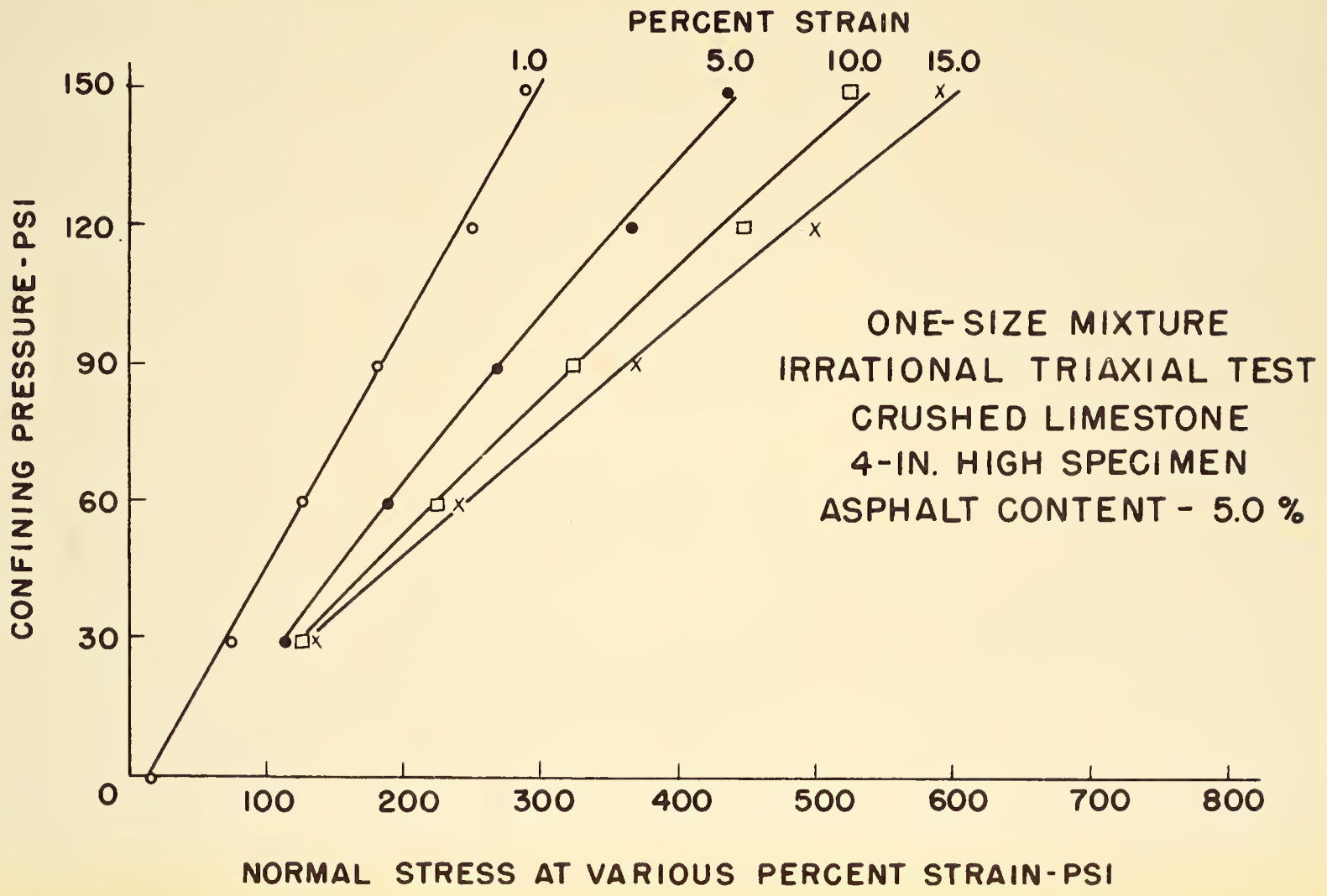

FIG. 13

is a true representation of its strength.

Type of Aggregate. In evaluating the variable of aggregate type for rational triaxial testing at high confining pressures, 10-in. high specimens were formed from uncrushed gravel at asphalt contents of 4.0 and 5.0 percent by weight of the total mixture. A comparison of the triaxial strengths at 10.0 percent strain of these specimens with the corresponding values obtained from crushed limestone specimens having identical grading and asphalt contents is presented in Figure 14 for 30, 90, and 150 psi confining pressures. This comparison is based upon the selection of 10.0 percent strain as the failure criterion for the one-size mixture.

The crushed limestone produced the greater shearing strengths for the two one-size mixtures throughout the range of confining pressures. This was attributed to the larger degree of interlocking among these angular aggregate particles than occurred with the uncrushed gravel. As was the case for the open-graded mixture, the difference in shearing strength between comparable mixtures of the uncrushed and crushed aggregates was less the higher the confining pressure, particularly when this difference is expressed as a percentage of the shearing strength of either mixture.

Asphalt Content. The effects of high confining pressure on the rational triaxial stability were determined for the one-size mixture having asphalt contents of 3.0, 4.0, and 5.0 percent by weight of the total mixture. The results of these tests for the crushed-limestone and uncrushed-gravel mixtures are presented in Tables 8 and 9, respectively (Appendix). The results of the rational triaxial tests for the low and

CONFINING PRESSURE VS. NORMAL STRESS AT 10.0 PERCENT STRAIN

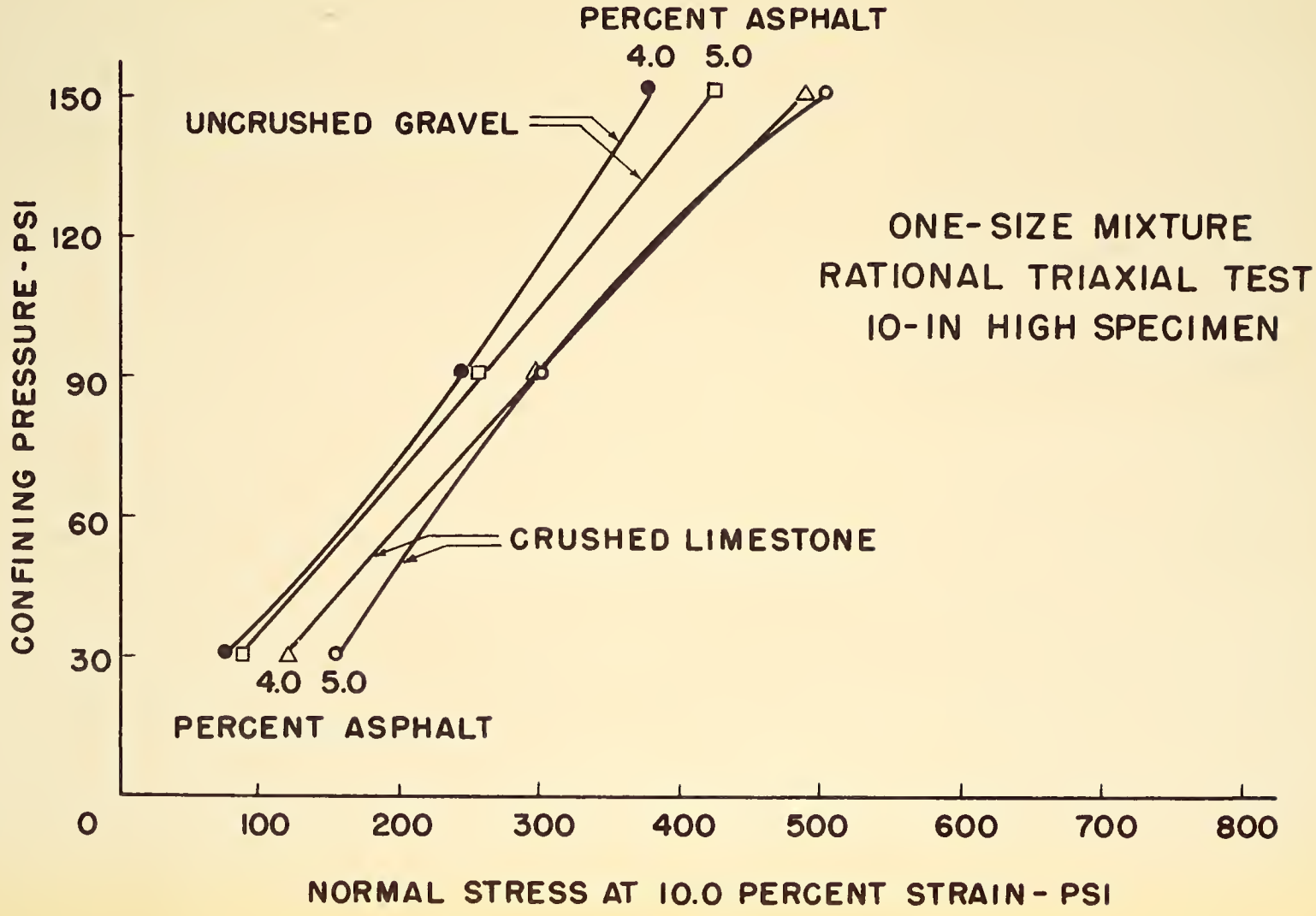

FIG. 14

high confining pressures of 30 and 150 psi, respectively, are presented in Figure 15 for the crushed-limestone specimens. The similar case for the uncrushed-gravel specimens is shown in Figure 16. For the failure criterion of 10.0 percent strain and for both types of aggregate, these results show that the confining pressure has little or no effect on the determination of asphalt content for maximum strength. The maximum triaxial stability was reached at an asphalt content near five percent by weight of the total mixture for both the crushed-limestone and the uncrushed-gravel mixtures of the one-size grading.

NORMAL STRESS AT 10.0 PERCENT STRAIN VS. ASPHALT CONTENT

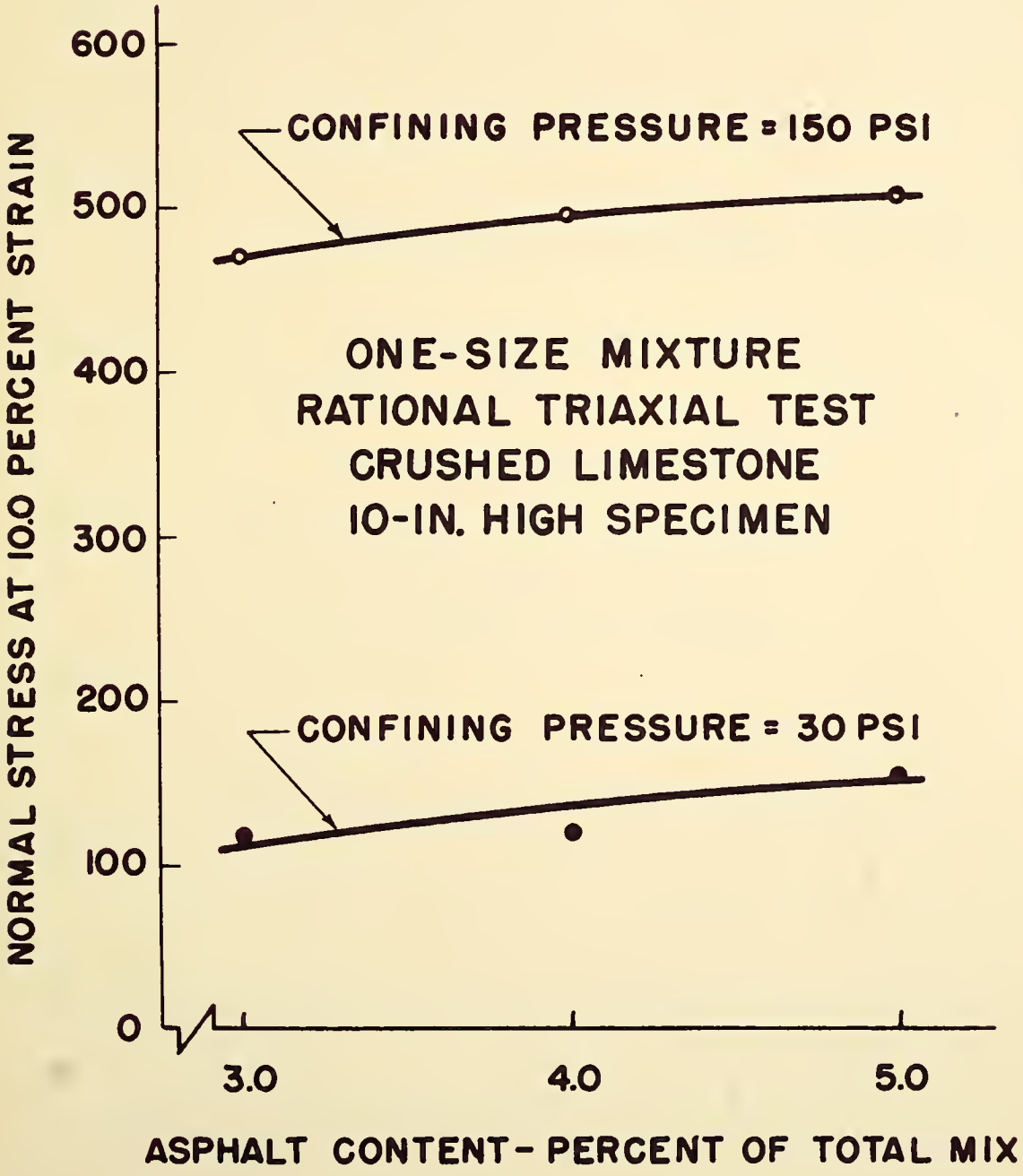

FIG. 15

NORMAL STRESS AT 10.0 PERCENT STRAIN VS. ASPHALT CONTENT

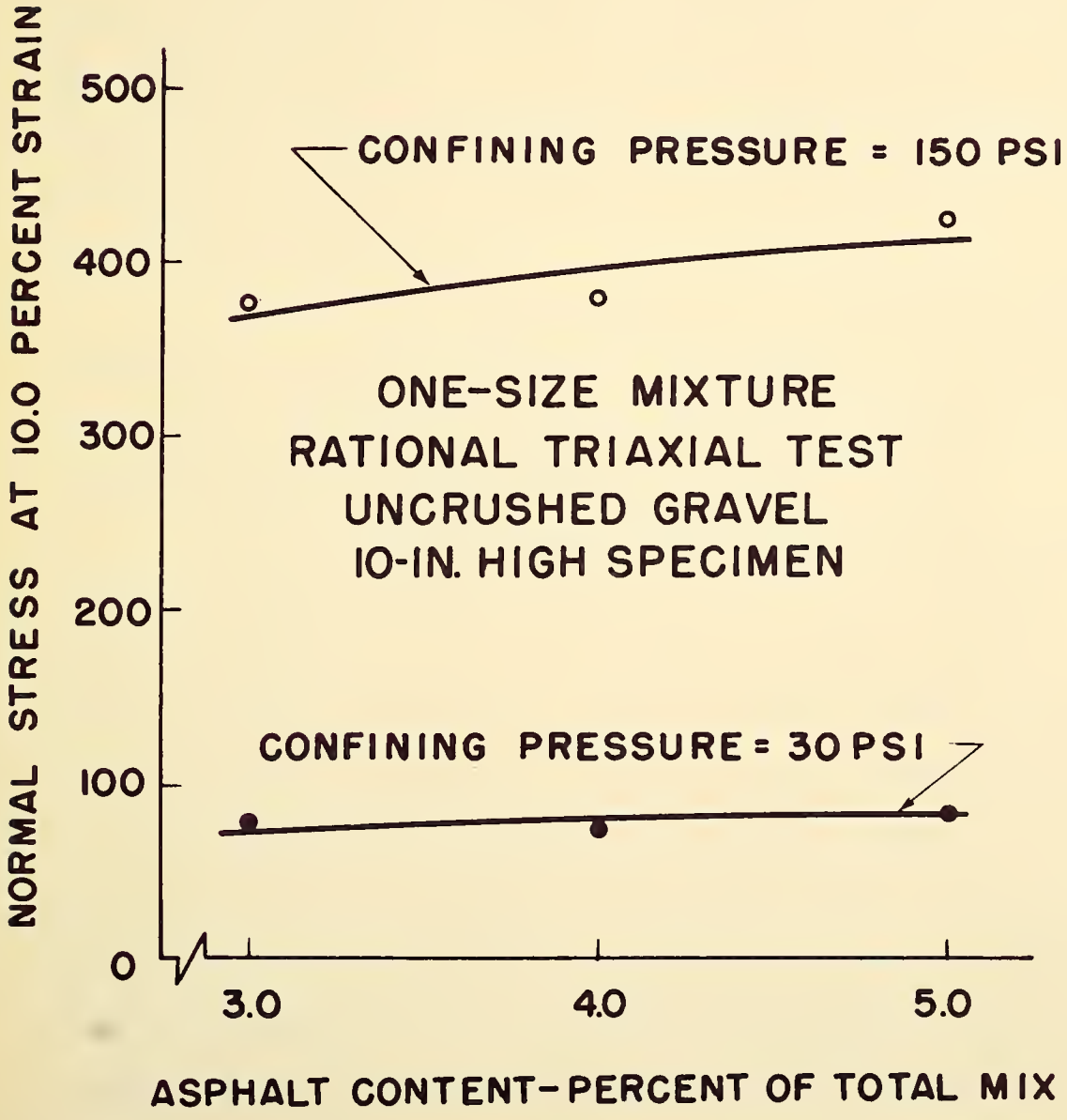

FIG. 16

SUMMARY OF RESULTS AND CONCLUSIONS

The following conclusions are drawn from the results of this laboratory investigation. Specifically, they are valid only for the bituminous-aggregate mixtures of the same materials and gradings and the designated testing methods that were utilized in this study.

1. The stress-strain curves representing the open-graded mixture were considerably different from those for the one-size mixture. The stress-strain diagrams for the open-graded mixture reached a peak normal stress value at a relatively low strain, while the normal stress continued to increase at a decreasing rate with an increase in the strain value for the one-size mixture.

2. When the open-graded mixture was evaluated by the rational triaxial test at high confining pressures, the shearing strength developed was accurately predicted by the Coulomb equation and represented by the constant parameters, cohesion, and angle of internal friction.

3. The irrational triaxial tests on this open-graded mixture produced a linear Mohr rupture envelope for the range of confining pressures investigated. However, the shearing strength values were higher than those obtained by the rational procedures because additional lateral support was afforded the short test specimens by the shearing stresses developed between the ends of the compacted specimen and the loading plates. Also, the slopes of these linear stress relationships of the rational and the irrational triaxial tests on the open-graded mixture were not the same; thus, indicating that different values of cohesion and angle of internal friction were produced by these two testing procedures.

4. In both the rational and the irrational triaxial tests, low values of shearing stress were developed by the one-size mixture at low strain values and low confining pressures. However, when the specimen deformation and/or the confining pressure were increased, sufficient shearing resistance was developed to indicate more realistic stability values for this paving mixture.

5. The triaxial compression tests at the low, intermediate, and high confining pressures showed that the more angular aggregate, crushed limestone, produced a larger resistance to shear than the more rounded aggregate, uncrushed gravel, for both the open-graded and one-size mixtures. However, this difference was less the higher the confining pressure, particularly when expressed as a percent of the shearing resistance of specimens of either material.

6. For both the open-graded and one-size paving mixtures, the asphalt content which gave maximum stability essentiallly was independent of the confining pressure used (30 - 150 psi).

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APPENDIX

TABLE 2

Triaxial Test Results — Open-Graded Mixture

Crushed Limestone — 10-in. High Specimen

Asphalt Content - 5.0%

Confining Pressure psi	Normal Stress - psi			Density lb/cu ft
	1.0% Strain	5.0% Strain	Peak	
0	---	---	164	148.2
0	---	---	168	146.8
0 (avg)	---	---	166	147.5
30	387	---	396	146.7
30	377	---	384	146.7
30 (avg)	382	---	390	146.7
60	431	---	445	147.4
60	434	---	455	147.3
60 (avg)	433	---	450	147.4
90	498	---	535	147.7
90	483	---	533	149.2
90 (avg)	491	---	534	148.5
120	492	586	590	146.7
120	512	594	594	146.3
120 (avg)	502	590	592	146.5
150	592	734	739	145.9
150	571	719	726	145.2
150 (avg)	582	727	733	145.6

TABLE 3

Triaxial Test Results — Open-Graded Mixture

Crushed Limestone — 4-in. High Specimen

Asphalt Content - 5.0%

Confining Pressure psi	Normal Stress psi	Density lb/cu ft
0	286	148.1
30	404	149.2
60	488	143.2
90	626	142.9
120	765	143.0
150	840	142.8

TABLE 4

Triaxial Test Results — Open-Graded Mixture

Crushed Limestone — 10-in. High Specimen

Confining Pressure psi	4.0% Asphalt		5.0% Asphalt		6.0% Asphalt	
	Normal Stress psi	Density lb/cu ft	Normal Stress psi	Density lb/cu ft	Normal Stress psi	Density lb/cu ft
30	245	144.0	390	146.7	211	147.6
90	500	145.0	534	148.5	—	—
150	722	143.9	733	145.6	669	147.7

TABLE 5

Triaxial Test Results — Open-Graded Mixture

Uncrushed Gravel — 10-in. High Specimen

Confining Pressure psi	4.0% Asphalt		5.0% Asphalt		6.0% Asphalt	
	Normal Stress psi	Density lb/cu ft	Normal Stress psi	Density lb/cu ft	Normal Stress psi	Density lb/cu ft
30	155	142.0	179	143.3	158	143.1
90	400	140.0	416	141.6	—	—
150	667	142.1	660	145.2	530	147.4

TABLE 6

Triaxial Test Results — One-Size Mixture

Crushed Limestone — 10-in. High Specimen

Asphalt Content - 5.0%

Confining Pressure psi	Normal Stress - psi				Density - lb/cu ft			C* in.^{3}/in.
	1.0% Strain	5.0% Strain	10.0% Strain	15.0% Strain	Before Test	After Test	Increase	
0	10	—	—	—	113.2	113.2	0.0	0.0
0	17	—	—	—	115.0	115.0	0.0	0.0
0 (avg)	14	—	—	—	114.1	114.1	0.0	0.0
30	99	141	154	158	112.9	113.4	0.5	1.20
30	106	143	154	156	111.7	112.2	0.5	1.26
30 (avg)	103	142	154	157	112.3	112.8	0.5	1.23
60	177	233	250	254	113.6	114.1	0.5	1.07
60	170	233	254	262	113.4	114.3	0.9	1.86
60 (avg)	174	233	252	258	113.5	114.2	0.7	1.47
90	226	282	314	324	113.8	115.2	1.4	0.98
90	223	274	290	332	113.4	114.2	0.8	0.60
90 (avg)	225	278	302	328	113.6	114.7	1.1	0.79
120	240	344	400	419	116.0	121.2	5.2	2.76
120	245	324	383	421	113.3	116.2	2.9	2.19
120 (avg)	243	334	392	420	114.7	118.7	4.0	2.48
150	296	429	511	540	115.3	117.2	1.9	1.46
150	310	414	497	536	115.1	120.9	5.8	6.10
150 (avg)	303	422	504	538	115.2	119.1	3.9	3.78

* C - change in volume per change in height

TABLE 7

Triaxial Test Results — One-Size Mixture

Crushed Limestone — 4-in. High Specimen

Asphalt Content - 5.0%

Confining Pressure psi	Normal Stress - psi				Density - lb/cu ft			C* $in.^3/in.$
	1.0% Strain	5.0% Strain	10.0% Strain	15.0% Strain	Before Test	After Test	Increase	
0	15	---	---	---	111.8	111.8	0.0	0.0
30	73	113	125	133	114.6	114.7	0.1	0.21
60	126	189	225	240	110.2	113.1	2.9	2.25
90	180	268	324	369	110.1	115.1	5.0	2.57
120	250	366	449	498	112.2	116.9	4.7	3.40
150	268	436	524	590	111.9	113.4	1.5	1.57

* C - change in volume per change in height

TABLE 8

Triaxial Test Results — One-Size Mixture

Crushed Limestone — 10-in. High Specimen

Confining Pressure psi	Normal Stress - psi				Density - lb/cu ft			C* $in.^3/in.$
	1.0% Strain	5.0% Strain	10.0% Strain	15.0% Strain	Before Test	After Test	Increase	
Asphalt Content - 5.0%								
30	103	142	154	157	112.3	112.8	0.5	1.23
90	225	278	302	328	113.6	114.7	1.1	0.79
150	303	422	504	538	115.2	119.1	3.9	3.78
Asphalt Content - 4.0%								
30	76	106	122	127	112.8	114.4	1.6	1.20
90	192	266	302	323	108.8	111.6	2.8	2.19
150	302	416	493	532	111.6	117.7	6.1	4.30
Asphalt Content - 3.0%								
30	78	105	118	126	111.1	113.9	2.8	2.11
150	289	391	469	520	110.4	115.0	4.6	4.06

* C - change in volume per change in height

TABLE 9

Triaxial Test Results — One-Size Mixture

Uncrushed Gravel — 10-in. High Specimen

Confining Pressure psi	Normal Stress - psi				Density - lb/cu ft			C* $\frac{3}{\text{in.}}/\text{in.}$
	1.0% Strain	5.0% Strain	10.0% Strain	15.0% Strain	Before Test	After Test	Increase	
Asphalt Content - 5.0%								
30	56	79	83	84	111.9	112.3	0.4	0.23
90	167	232	258	282	113.6	114.2	0.6	0.52
150	262	374	423	441	113.0	114.4	1.4	1.17
Asphalt Content - 4.0%								
30	58	72	75	75	112.7	113.6	0.9	0.16
90	165	222	246	256	112.1	113.1	1.0	2.46
150	247	332	379	406	113.2	114.5	1.3	1.01
Asphalt Content - 3.0%								
30	56	72	79	85	113.0	114.3	1.3	0.89
150	262	340	378	400	113.1	114.6	1.5	1.38

* C - change in volume per change in height